QBO as potential amplifier of solar cycle influence

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[1] The solar cycle (SC) effect in the lower atmosphere has been linked observationally to the quasi-biennial oscillation (QBO) of the zonal circulation. Salby and Callaghan (2000) in particular analyzed the QBO covering more than 40 years and found that it contains a large SC signature at 20 km. We discuss a 3D study in which we simulate the QBO under the influence of the SC. For a SC period of 10 years, the relative amplitude of radiative forcing is taken to vary with height: 0.2% (surface), 2% (50 km), 20% (100 km and above). This model produces in the lower stratosphere a relatively large modulation of the QBO, which appears to come from the SC and qualitatively agrees with the observations. The modulation of the QBO, with constant phase relative to the SC, is shown to persist at least for 50 years, and it is induced by a SC modulated annual oscillation that is hemispherically symmetric and confined to low latitudes (Mayr et al., 2005). **Citation:** Mayr, H. G., J. G. Mengel, C. L. Wolff, and H. S. Porter (2006), QBO as potential amplifier of solar cycle influence, *Geophys. Res. Lett.*, *33*, L05812, doi:10.1029/2005GL025650.

1. Introduction

[2] *Labitzke* [1982, 1987] and *Labitzke and Van Loon* [1988, 1992] discovered that the temperatures at northern polar latitudes in winter are positively and negatively correlated with the solar cycle (SC) when the quasi-biennial oscillation (QBO) of the zonal circulation is in its negative and positive phase respectively. At mid-latitudes they observed opposite correlations. *Dunkerton and Baldwin* [1992] and *Baldwin and Dunkerton* [1998] found evidence of a quasi-decadal oscillation correlated with the QBO and SC.

[3] *Salby and Callaghan* [2000] analyzed the 40-year record of the observed QBO zonal winds at about 20 km altitude. The power spectrum in their Figure 1 shows a sharp peak at 0.41 cycles per year (cpy), corresponding to a QBO period of about 29 months. Smaller neighboring maxima in the spectrum at 0.5 and 0.59 cpy reveal difference frequencies that represent the 11-year SC modulation of the QBO and its second harmonic of 5.5 years. To isolate the SC signature, Salby and Callaghan synthesized the QBO with its spectral side-lobes. It shows that, correlated with the SC, the wind power at 20 km varies from about 150 to 400 m^2/s^2, corresponding to a large variation in the winds from about 12 to 20 m/s. Analyzing 50 years of wind observations, *Hamilton* [2002] confirmed the quasi-decadal modulation inferred by Salby and Callaghan but concluded that the connection to the SC is not as clear in the extended data record.

[4] The observations by *Salby and Callaghan* [2000] were the stimulus for the 3D modeling study discussed here, in which we simulate the SC modulation of the QBO.

2. Wave Driven Quasi-Biennial Oscillation (QBO)

[5] The QBO, with periods between 22 and 34 months and reviewed by *Baldwin et al.* [2001], is confined to low latitudes where it dominates the zonal circulation of the lower stratosphere. Associated with the QBO is the semi-annual oscillation (SAO), which dominates the equatorial circulation of the upper stratosphere and mesosphere [*Hirota*, 1980]. It was demonstrated by *Lindzen and Holton* [1968], *Holton and Lindzen* [1972], and others [e.g., *Plumb*, 1977; *Dunkerton*, 1985] for the QBO, and by *Dunkerton* [1979] and *Hamilton* [1986] for the SAO, that these equatorial oscillations can be driven by planetary waves. More recently, modeling studies with observed planetary waves have led to the conclusion that small-scale gravity waves (GW) appear to be more important [e.g., *Hitchman and Leovy*, 1988]. Except for a few attempts at simulating the QBO with resolved GWs [e.g., *Takahashi*, 1999], these waves need to be parameterized for global-scale models [e.g., *Giorgetta et al.*, 2002]. Applying the GW parameterization of *Hines* [1997a, 1997b], we were among the first to reproduce with our Numerical Spectral Model (NSM) the QBO and SAO [e.g., *Mengel et al.*, 1995; *Mayr et al.*, 1997]. In agreement with our model results, the analysis of *Haynes* [1998] showed how a globally uniform wave source can generate the zonal circulation of the QBO confined to low latitudes as observed.

[6] The QBO amplitude and its period are strongly influenced by external time dependent forcing. In the seminal theory for the QBO by *Lindzen and Holton* [1968], the seasonal cycle and resulting SAO were invoked to seed, and thereby influence the QBO. This influence was confirmed with a 2D study [*Mayr et al.*, 1998], where QBO like oscillations were generated, (a) for perpetual equinox and (b) with the seasonal cycle of solar heating. The seasonal cycle lengthened the period of the QBO from 17 to 21 months and more than doubled its amplitude in the lower stratosphere.

[7] Driven by waves, but strongly influenced by the seasonal variations, the QBO then could be affected significantly also by the SC whose signature then would extend to lower altitudes. Two factors are important for this. First, at equatorial latitudes where the Coriolis force vanishes, the wave source accelerates primarily the zonal winds without

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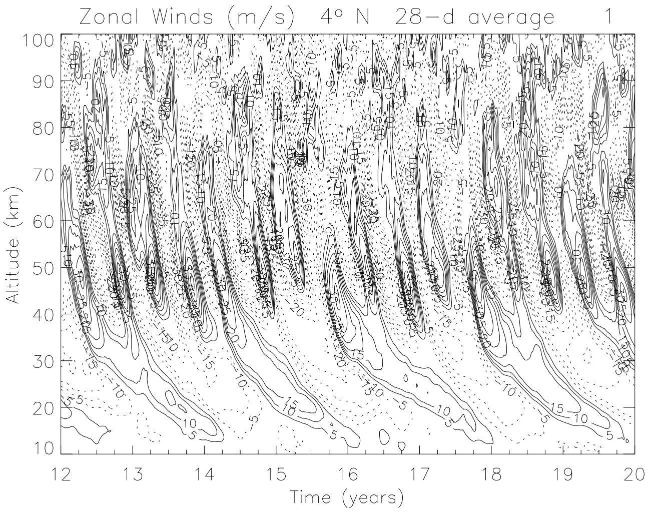

Figure 1. Computed zonal winds near the equator show the QBO with a period close to 24 months and almost 20 m/s amplitude at 30 km. Higher up, the SAO dominates with zonal wind amplitudes exceeding 30 m/s.

generating a meridional circulation that would normally tend to redistribute the flow momentum. The flow thus is essentially trapped around the equator, where wave interaction and diffusion cause the QBO to propagate down. Second, the time constant for eddy diffusion in the lower stratosphere is on the order of years, which favors the generation of SC variations at lower altitudes.

[8] *Mayr et al.* [2003] conducted two studies to explore this mechanism. A 2D model (zonal wave number $m = 0$) was run in each case with and without the SC, and the differences in the zonal winds were analyzed. In the first study, the QBO had a period of 30 months, which is exceptionally stable because it is synchronized by the seasonal cycle. The SC then modulated only the QBO amplitude, and the effect was relatively small. In the second case, the QBO period of ~33 months was variable. The SC then affected not only the amplitude of the QBO but its phase and periodicity as well, which produced large differences in the winds.

3. 3D Modeling Study With QBO and Solar Cycle (SC) Influence

[9] Following up on the above 2D study, we carried out a 3D simulation with the NSM, in which we isolate the SC modulation of the QBO for comparison with the observations by *Salby and Callaghan* [2000]. With a 10-year SC, the amplitude of relative variation in the solar forcing for the zonal mean ($m = 0$) is taken to be 0.2% at the surface, 2% at 50 km, and 20% at 100 km and above.

3.1. Numerical Spectral Model (NSM)

[10] The NSM was introduced by *Chan et al.* [1994], and 2D as well as 3D applications were employed to describe the QBO and SAO, and the tides and planetary waves in the middle atmosphere [e.g., *Mengel et al.*, 1995; *Mayr et al.*, 1997, 2003; *Mayr and Mengel*, 2005]. For the zonal mean, the NSM is driven by the absorption of EUV and UV radiation, with the heating rates taken from *Strobel* [1978]. A time independent heat source in the upper troposphere for $m = 0$ reproduces qualitatively the observed zonal jets and temperature variations near the tropopause. The radiative loss is described in terms of Newtonian cooling. We adopt the parameterization developed by *Zhu* [1989] but modify it to keep the radiative relaxation rate constant below 20 km. For the tides, the heating rates are taken from *Forbes and Garrett* [1978]. Since the model does not have topography, the planetary waves are generated solely by instabilities.

[11] The NSM incorporates the Doppler Spread Parameterization (DSP) for GWs developed by *Hines* [1997a, 1997b]. The DSP deals with a spectrum of waves that interact with each other to produce Doppler spreading, which affects the wave interaction with the flow. To account for enhanced wave activity in the tropics, a latitude dependent tropospheric GW source is adopted that peaks at the equator. The source is isotropic and time independent.

[12] The NSM is integrated from the surface to 130 km with a vertical step size of about 0.5 km, and it is truncated at the meridional and zonal wave numbers $l = 12$ and $m = 4$, respectively. With the initial conditions set to zero, the model was run with and without the SC.

3.2. 3D Model Results

[13] As shown in Figure 1, the zonal winds for the QBO and SAO near the equator are fairly realistic. With a QBO period close to 24 months, the winds are almost 20 m/s at 30 km, and at 50 km the amplitudes for the SAO exceed 30 m/s.

[14] In Figure 2a, we show the spectrum from the computer run with SC, covering a period from 10 to 40 years (allowing for spin up, the first 10 years are ignored). The QBO is well defined at harmonic h = 16, which represents a period of 22.5 months for this 30-year time span, i.e., 360 months/16. Although the SC signatures

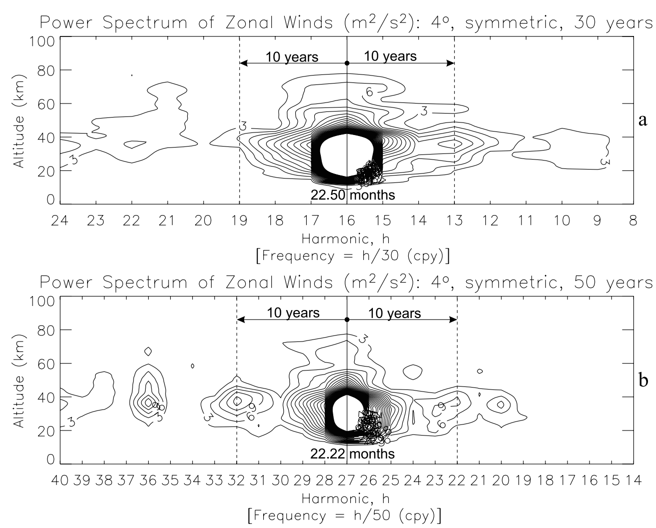

Figure 2. Spectra in terms of discrete Fourier harmonics, h, which are related to the frequency ν = h/y (cpy) in units of cycles per year (y). (a) For the 30-year time span, the QBO at h = 16 represents a 22.5-month period, and the signatures of the 10-year SC modulation occur at h = 16 ± 3. (b) The spectral harmonics for 50 years are h = 27 for the 22.22-month QBO, and h = 27 ± 5 for the SC.

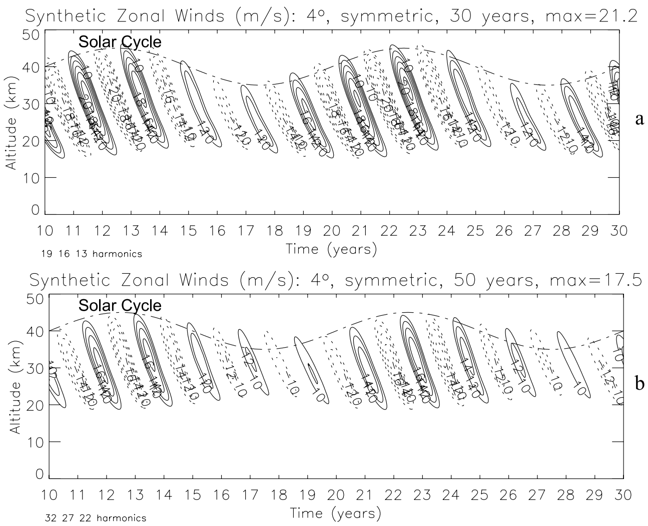

Figure 3. Syntheses for the 3 harmonics that describe the 10-year modulations of the QBO; that is, (a) h = 16 with (16 ± 3) and (b) h = 27 with (27 ± 5). With contour intervals of 2 m/s, the lowest level shown is 10 m/s. The QBO amplitudes vary at 30 km from about 10 to 18 m/s, which is in qualitative agreement with the observations by *Salby and Callaghan* [2000]. For both time spans (30 and 50 years), the amplitude modulations of the QBO have similar magnitudes, and their phase relationship relative to the SC is the same.

are not pronounced, a side lobe for the 10-year modulation appears at h = 13 (16 − 3), and the next harmonic is also visible at h = 22 (16 + 6), representing the 5-year component. To demonstrate that the SC signature is robust, we present also the results from a computer run extended to 60 years. Ignoring again the first 10 years, we show in Figure 2b the spectrum for the 50-year time span. In this case, the QBO is defined by the harmonic h = 27, with a period of 22.22 months – and pronounced SC signatures appear in the side lobes at h = 22 (27 − 5) and in particular at h = 32 (27 + 5).

[15] Corresponding to the spectra shown in Figure 2, we present in Figure 3 the syntheses of the QBO with the 10-year side lobes that describe the SC signatures. For both the 30 (Figure 3a) and 50 (Figure 3b) year time spans analyzed, the magnitude of the computed SC modulation is relatively large, causing the QBO amplitude to vary at 30 km from about 12 to 21 m/s (Figure 3a) and from 10 to 17 m/s (Figure 3b). Without the SC (not shown), the irregular 10-year side lobes around the QBO cause variations that are small or erratic, reflecting the lack of systematic SC forcing. For comparison, we present in Figure 3 with dashed lines the phase of the imposed SC heating. From this it is apparent that the peak of the QBO, in both cases (Figures 3a and 3b), occurs close to the SC maximum. For at least 50 years, the SC produces persistent QBO modulations. The amplitudes are of comparable magnitude, and the phase relationship relative to the variable solar forcing is the same.

[16] Although the QBO is generated in the equatorial region, its signatures extend to high latitudes. This is shown with Figure 4a where we present the spectrum from the 50-year time span for the temperature variations near the pole. In Figure 4b the synthesis is shown for the 10-year modulations of the QBO. For the 30 year time span (not shown), the patterns are similar. Although the computed SC signatures are small, <1 K, they appear in the troposphere below 10 km. We do not yet understand how the temperature effect is generated exactly. The meridional circulation could produce the effect in principle, but the planetary waves are likely involved too.

4. Summary and Conclusions

[17] The impetus for the present study has been the paper by *Salby and Callaghan* [2000], which showed that the observed QBO exhibits a relatively large SC signature. Our 3D model results (Figures 2 and 3) reproduce qualitatively the observed variations of the zonal winds in the lower stratosphere near the equator. A small SC signature is also generated in the tropospheric temperature near the poles (Figure 4).

[18] The question is what causes the SC modulation of the QBO in our model, and *Mayr et al.* [2005] provide an answer. It is shown there that the same 3D model run generates a hemispherically symmetric annual oscillation (AO, with 12-month period), which is confined to low latitudes and is referred to as Equatorial Annual Oscillation (EAO). Though weak compared with the dominant anti-symmetric AO, the EAO is strongly modulated by the SC, and the modulation is in phase with the SC modulation of the QBO (see *Mayr et al.* [2005, Figure 1] for comparison). The EAO originates at around 60 km and evidently acts as the pathway and pacemaker for the SC influence on the QBO. Induced by the EAO, the SC influence on the QBO is apparently amplified and transferred to lower altitudes by

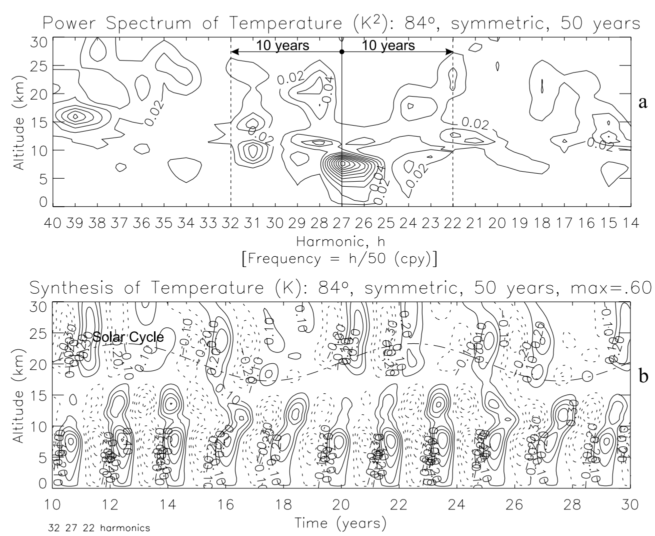

Figure 4. (a) Computed spectrum for the temperature variations from the 50-year time span reveal QBO and SC signatures at around 10 km in the polar region. (b) The synthesis of the spectral features for the QBO with 10-year side lobes corresponding to Figure 3b. With contour intervals of 0.1 K, a weak (<1 K) SC modulation of the QBO appears in the troposphere.

tapping the momentum from the upward propagating GWs. In this process, a SC modulation of the QBO period could prove to be very effective, as our earlier 2D study indicated [*Mayr et al.*, 2003].

[19] Although the above mechanism can simulate the observations qualitatively, the model we present is still simplified. Our QBO period of about 22 months is comparatively short and less variable than observed. With a constant SC period of 10 years, the maximum of the cycle occurs during northern summer solstice, which synchronizes the solar variability and the seasonal variations. In reality, the period of the SC is variable, and so is its magnitude. The model also does not account for the feedback involving ozone for example, which apparently produces another pathway for the SC influence through the QBO [*Cordero and Nathan*, 2005].

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